DEVELOPMENT OF TEMPERATURE SENSITIVE PAINTS FOR THE DETECTION OF SMALL TEMPERATURE DIFFERENCES

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ABSTRACT

Temperature sensitive paints (TSP's) have recently been used to detect small temperature differences on aerodynamic model surfaces. These types of applications impose stringent performance requirements on a paint system. The TSP's must operate over a broad temperature range, must be physically robust (cannot chip or peel), must be polishable to at least the smoothness of the model surface, and must have sufficient sensitivity to detect small temperature differences. TSP coatings based on the use of metal complexes in polymer binders were developed at NASA Langley Research Center which meet most of the requirements for detection of small temperature differences under severe environmental conditions.

INTRODUCTION

Sullivan et al. have recently tested numerous temperature sensitive paint (TSP) formulations for the measurement of model surface temperatures in wind tunnel tests (4, 5, 6, 7, 8, 9). McLachlan et al. also demonstrated the use of TSP to derive boundary layer transition locations based on the change in heat transfer characteristics that accompany boundary layer transitions (10). The technique involves painting the model with a TSP (usually by spraying multiple coats), illuminating the model with light having the wavelength necessary to excite the luminescent compound in the paint, monitoring the luminescent intensity with a scientific grade CCD video camera, and enhancing the image through digital processing. This is represented by Figure 1. This application of TSP requires paints which are sensitive to very small temperature differences (9). Sullivan et al. tested techniques for enhancing the temperature difference across the boundary (9). They showed that the temperature difference may be enhanced by either changing the temperature of the tunnel windstream (transient method) or by heating the model (steady method). Sullivan tested both non-metallic models and stainless steel models. When steel models are used it is necessary to apply a base coat under the TSP which serves as a thermal insulator. Although Sullivan et al. demonstrated that sensitive TSP can be used to visualize transition boundaries, some problems were encountered with physical defects developing in the paints.

A TSP suitable for detecting small temperature differences in aerodynamic testing must meet the following performance requirements:

- The paint must be sensitive to very small changes in temperature.
- The paint must be robust. It must adhere to polished steel models over a broad temperature range and over a wide range of wind speeds.
- The paint must be polishable to the desired smoothness.
- The paint must be easily applied over a large surface area.
- The paint must be removable without damaging the finish to which it is applied.

There were three phases to developing a TSP system would meet the required performance specifications.

- Develop a paint system which is physically robust (maintain integrity at all required temperatures and wind speeds).

- Demonstrate the performance of the paint system under laboratory test conditions with respect to temperature sensitivity, smoothness, and physical integrity.

- Test new TSP technology under the physical requirements of tunnel conditions. These requirements included the following:

    - Limited optical access for lights and camera
    - Model motion

Since test conditions may cover a broad temperature range, more than one luminophore is needed in order to have the sensitivity required to detect small temperature differences. For example, if the tempeature range of interest is 120°C one luminophore with a linear temperature sensitivity over this entire range and a 90% decrease in light emission would have a theoretical sensitivity of about 0.75% change in emission per degree. However, if the 120° range is divided into two parts and two different luminophores are used, each having a 90% change in emission over its particular 60° range, the paint sensitivity to temperature in that range would be about 1.5% change in emission per degree. This significantly increases the probability of seeing a small temperature difference. For this reason different TSP formulations were developed to cover a small portion of the total temperature range to be considered.

EXPERIMENTAL APPROACH

Paints were formulated from ruthenium metal complexes such as ruthenium(II) bypyridine chloride (Rubypy) or ruthenium(II) terpyridine chloride (Rutrpy) and a proprietary polymer binder. The TSP was sprayed over a white base coat which gave improved diffuse reflection.

Continuous lighting (CW) for the tests was supplied by small cylindrical (3" dia.) lamps constructed in-house. These lamps consist of an air-cooled housing, a 75 watt projector lamp, operating at 21 VDC at 3.65 amps, and filters necessary to produce the desired output wavelengths. A Photometrics CH-250, 14 bit, scientific grade CCD camera was used for data acquisition. Data processing was accomplished with temperature/pressure sensitive paint software written in Visual C^{++} and developed at LARC by Vigyan Corporation. A typical relative emission vs temperature plot is shown in Figure 2.

In order to verify that the TSP had sufficient sensitivity to detect very small temperature differences, a device was constructed which gave precise control of the temperature difference between two adjacent painted areas. This is shown in Figure 3. The device consists of two independently mounted copper test samples painted with TSP and equipped with heaters, each controlled by a separate power supply. A calibrated Platinum Resistance Thermometer (PRT) was bonded to the surface of each sample plate to accurately measure the test sample temperature. Initially, both samples were allowed to equilibrate at ambient temperature. The camera output signal was measured, and the power was applied to one side, starting with about 2 milliwatts of pulsed DC voltage. The average paint luminescence over an area 50 x 50 pixels square was measured at a level of 14000 out of 16383 gray levels in order to stay well above the camera noise level. All images were integdrated over a period of 300 milliseconds. As the temperature of one side increased another camera reading was taken. This was repeated in increments of approximately 0.01°C until the paint luminescence intensity decreased enough to be detected by the camera. This procedure established the Minimum Resolvable Temperature Difference (MRTD) for the paint at the particular ambient temperature. The MRTD was established over the temperature range of maximum response for the particular TSP of interest. Using this apparatus in a controlled temperature chamber, it was shown that a temperature difference of less than 0.1°C could be resolved if the paint had a temperature response of at least 0.7% change in emission per °C.

The potential for model motion in wind tunnel testing imposes an additional constraint on an optical measurement technique such as TSP if the measurement is location sensitive. Since this can be a concern in some applications of TSP, the use of flash illumination was investigated. In principle one could simply increase the effective camera shutter speed to stop subject motion. However, this requires a corresponding increase in illumination intensity which is difficult to achieve with continuous illumination. The intensity of illumination could be increased by using larger lamps. However, high output lamps are large and produce a lot of heat. Their size precludes use in many tunnels and the enormous heat load makes it difficult to sufficiently cool optical components. A 1000 watt theater lamp (8" wide x 30" long) was tested in a laboratory setup. No colored filter was found which would withstand the heat without forced air cooling and the intensity at a distance of 5 feet was not sufficient to give a satisfactory signal to noise using a camera shutter speed of one millisecond. Motion can just as readily be dealt with by the use of flash illumination. Flash illumination was supplied by an air-cooled flash lamp system developed in-house. The lamp was powered by a power supply capable of producing a 4000 watt-second pulse to the lamp. The flash duration was approximately 25 milliseconds. To compare the effectiveness of flash illumination with CW illumination both the continuous lamps and the flash lamps were positioned side-by-side perpendicular to the paint sample at a distance of one meter. The digital camera was aligned alongside the lamp housing. The Photometrics 14 bit CCD camera was used for image acquisition. The paint sample was adjusted to the desired temperature range. The camera output was optimized for near maximum digital output using the CW lighting and an exposure time of 100 milliseconds. After setting the camera sensitivity the sample output was measured and recorded. The CW lamp was then occluded and the flash lamp power level was adjusted to give the same signal as the CW illumination when the camera shutter was open. The camera shutter was opened for 2 seconds with the flash occurring at approximately the mid-point in the shutter cycle. The sample output was measured as a function of temperature using both CW and flash illumination. The LARC developed software was used for data and image processing. A comparison of the response curves obtained with CW and flash illumination is shown in Figure 4. No problems were encountered with luminophore response to the short duration excitation and the paint sensitivity was essentially the same as that obtained with continuous illumination.

RESULTS AND CONCLUSION

At the onset of the project it was felt that a large change in luminescence per degree change in temperature was necessary if a TSP was to be useful for the measurement of small temperature differences on aerodynamic model surfaces. This was found to be especially true under conditions where lighting and signal intensity at the camera are less than optimum. Laboratory tests have shown that TSP can be a useful tool for identifying the location of small temperature differences under severe test conditions. Model motion can best be dealt with using flash illumination.

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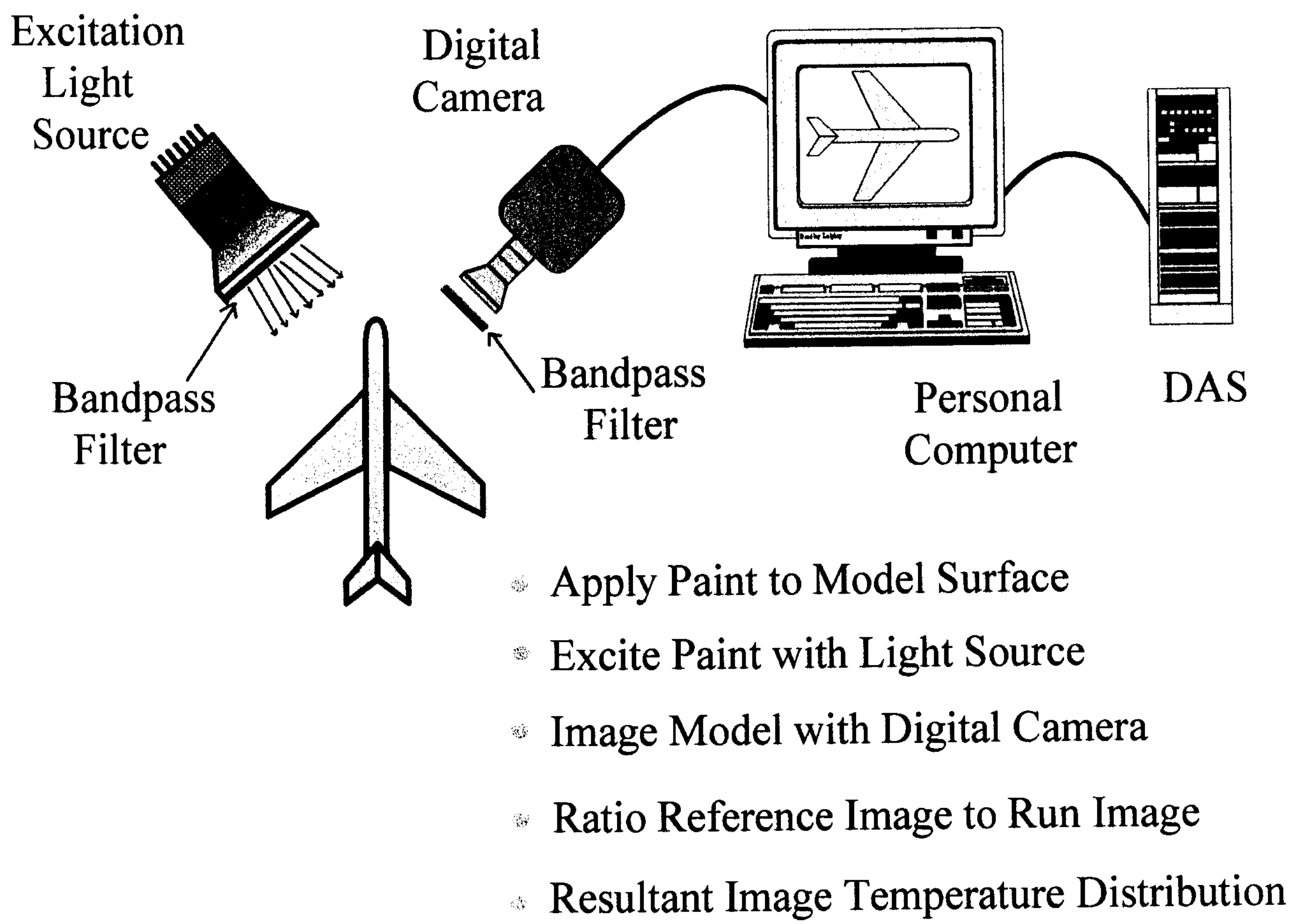

Figure 1. TSP System Configuration

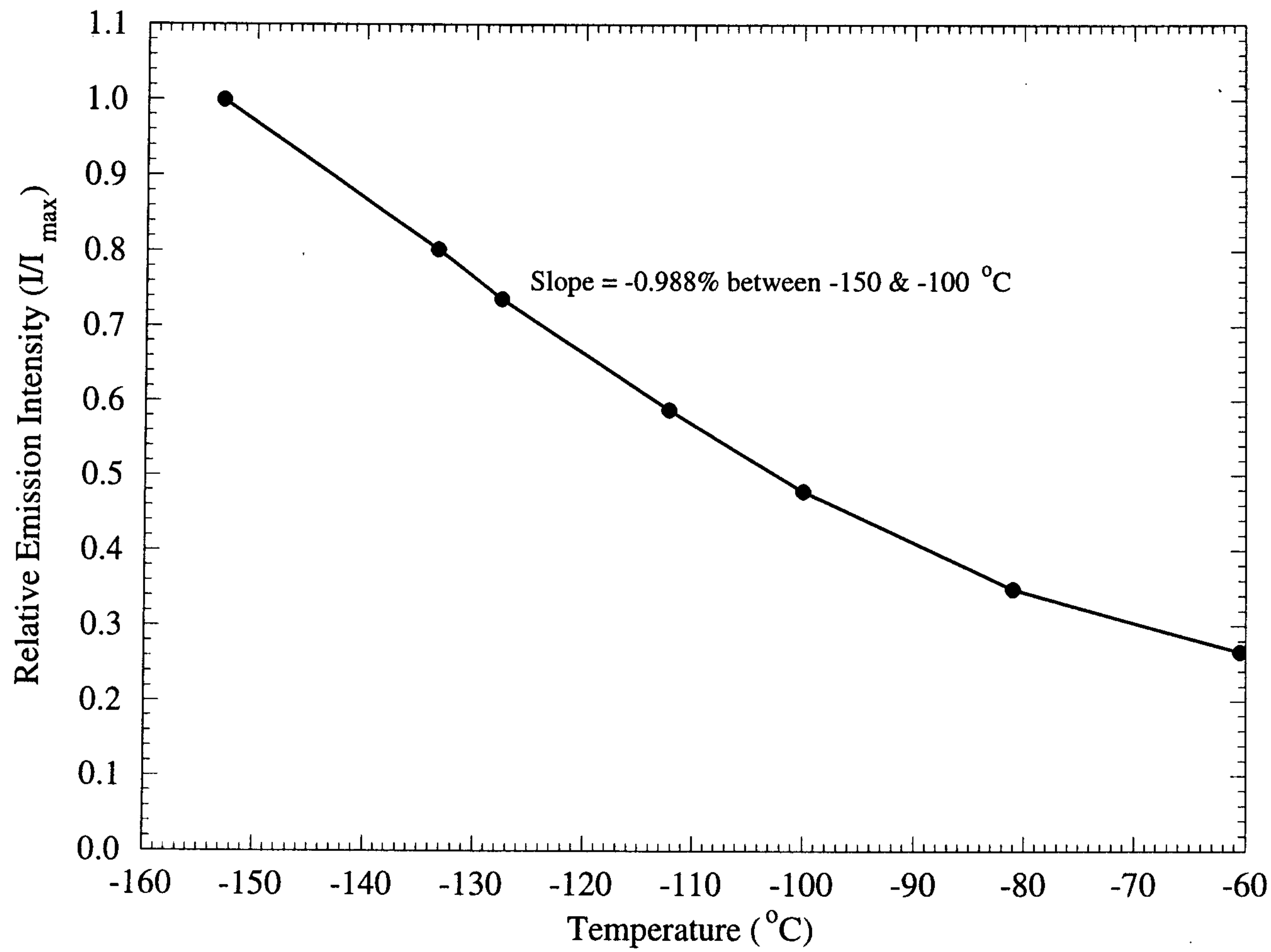

Figure 2. Relative Emission Intensity vs Temperature for Rutrpy Paint

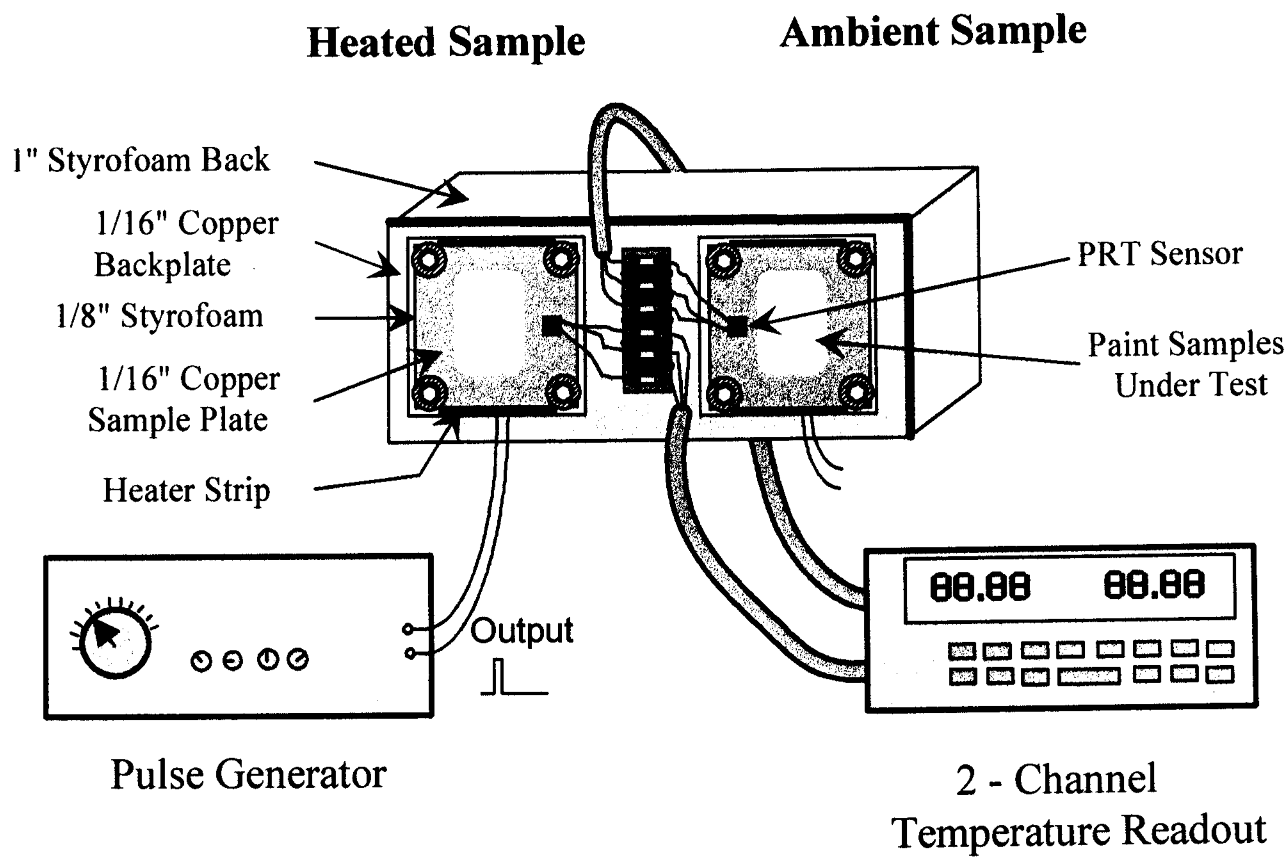

Figure 3. Temperature Difference Device

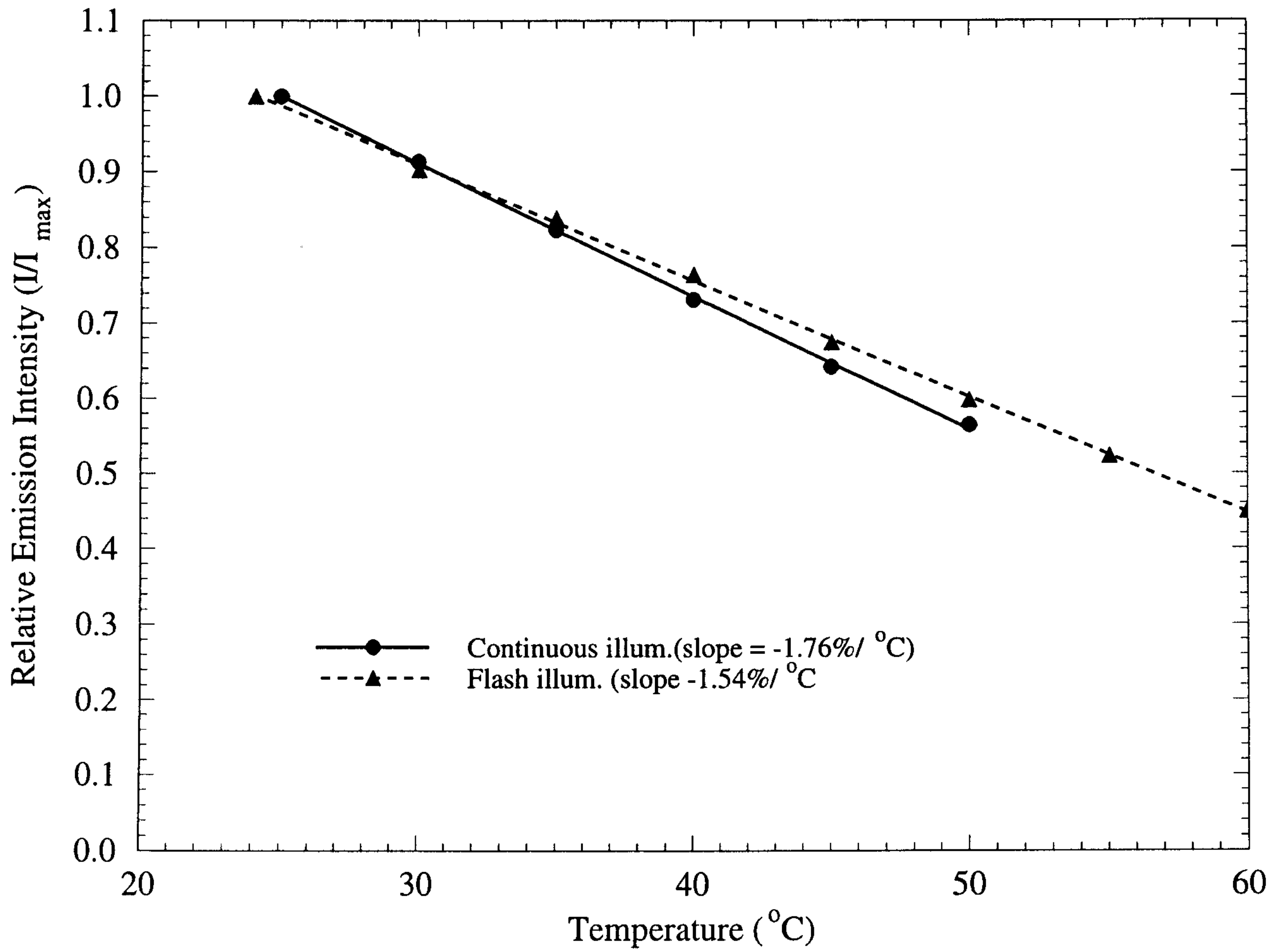

Figure 4. Comparison of Calibration Curves for Continuous and Flash Illumination for Rubypy TSP